Determination of Laminar Flame Speed of Diesel Fuel for Use in a Turbulent Flame Spread Premixed Combustion Model

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14. ABSTRACT

One of the key challenges facing diesel engine system modelers lies in adequately predicting the fuel burning rate profile given the direct relationship between energy release and key performance parameters such as fuel economy, torque, and exhaust emissions. Current state-of-the-art combustion sub-models employed in such system simulation codes rely heavily on empiricism and successful application of such sub-models for new engine designs is highly dependent on past experience with similar combustion systems. One common approach to address this issue is to expend great effort choosing associated empirical coefficients over a range of similar combustion system designs thus improving the potential predictive capability of a given empirical model. But continual combustion system development and design changes limit the extrapolation and application of such generic combustion system dependent coefficients to new designs due to various reasons including advancements in fuel injection systems, engine control strategy encompassing multiple injections, and combustion chamber geometry. In order to address these very difficult challenges, an extensive effort has been applied toward developing a physically based, simplified combustion model for military-relevant diesel engines known as the Large Scale Combustion Model (LSCM). Recent effort has been spent further refining the first stage of the LSCM two stage combustion model that is known as the premixed phase sub-model. This particular sub-model has been compared with high-speed cylinder pressure data acquired from two relevant direct injection diesel engines with much success based on a user defined parameter referred to as the laminar flame speed by the combustion community. It is a physically significant parameter that is highly dependent on local temperature, pressure, and oxygen concentration but little experimental effort has been spent determining its behavior for diesel fuel due to ignition constraints. This submission will discuss one approach of indirectly determining this key combustion parameter.

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NAC

Research & Advanced Engineering
Ford Motor Company

Cummins

FEV

Agenda

- Introduction
- Historical Perspective
- Modeling Effort
- Experimental Set-up
- Results
- Conclusion

Courtesy of Dr. M.-C. Lai
Wayne State University

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Introduction

COMBAT VEHICLES

- **M1 Abrams (AGT-1500)**
- **M109/M110 Self Propelled Howitzer (8V71T)**
- **M2/M3 Bradley (VTA-903)**
- **M88 Medium Recovery Vehicle (TCM-1790)**
- **M578 – Light Armored Recovery Vehicle (LRC) – (8V71T)**
- **M60 family (TCM-1790)**
- **Chaparral Missile Launcher (6V53T)**
- **FAASV – Fast Assault Ammunition Supply Vehicle (8V71T)**
- **M551 Sheridan Assault Vehicle (6V53T)**
- **Stryker (3126)**

TACTICAL VEHICLES

- **HET Heavy Equipment Transporter (8V92TA)**
- **HEMTT Heavy Expanded Mobility Tactical Truck (8V92TA)**
- **PLS Palletized Loading System (8V92TA)**
- **2.5 Ton Truck (LD-465/LDT-465)**
- **M939 5 Ton Truck (NHC 250/6CTA8.3)**
- **M915/M916 Line Hauler (NTC400/S-60)**
- **M917, M918, M919 Tractor (NTC 400)**
- **HMMWV (GM 6.2/6.5 IDI)**
- **CUCV Commercial Utility Cargo Vehicle (GM 6.2/6.5 IDI)**

LEGEND: **red: two-stroke diesel**   **white: four-stroke diesel**   **yellow: gas turbine**

Introduction

300,000 +   tactical and combat vehicles (150 – 1500 BHP)

240,000 +   trucks – class 2 thru class 8 + (150 – 500 BHP)

40,000   +   2-stroke powered vehicles (200 – 500 BHP)

PLS – Palletized Loading System

M113 Personal Carrier

HEMTT – Heavy Expanded Mobility Tactical Truck

*FVPDS (Jan. 2000)

Fielded Vehicle Performance Data Systems

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Introduction

Army ground vehicles comprised of predominately commercially derived diesel engines.

Historical Perspective on Diesel Combustion

- Droplet evaporation models – Tanasawa (1953) based on distribution function of Probert (1946)

- Injection rate/evaporation rate control model – Austen and Lyn (1961); "triangular burning rate model"

- Engine system simulation inclusion – Cook (1963), McAulay et al. (1965)

- Coupled droplet evaporation, mixing, and kinetics – Shipinski et al. (1969)
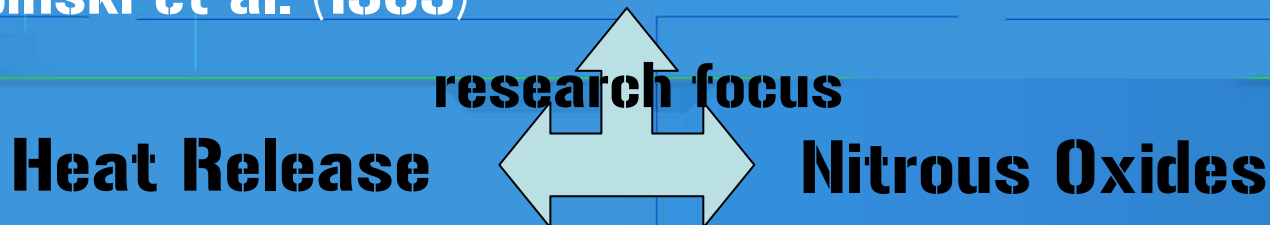
research focus

Heat Release ⟷ Nitrous Oxides

Historical Perspective on Diesel Combustion

- Global mixing models – Whitehouse and Way (1970-74), Grigg and Syed (1970), Khan et al. (1971)

- Thermodynamic multi-zone models (predecessor to CFD)
    - Bastress et al. (1971), Shahed et al. (1973), Hodgetts and Shroff (1975), Hiroyasu and Kodata (1976), Maguerdichian and Watson (1978)

- Focused bulk air-fuel mixing efforts:
    - Dent and Mehta (1981), Kono et al. (1985), Kyriakides et al. (1986), Schihl et al. (1996)

- Empirical heat release models
    - Watson (1977), Ghojel (1982), Miyamota et al. (1985), Craddock and Hussain (1986), Breuer (1995), Reddy et al. (1996)

Historical Perspective on Diesel Combustion

- Today there is STILL NOT an universally accepted combustion model for diesel sprays

- Previous study has shown a 1 – 10% error in fuel consumption for LD vehicles due combustion miss prediction

- Fidelity of model (0-D, 1-D, 2-D, 3-D) dependent on particular design issue in question

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Modeling Effort – TARDEC LSCM
(Large Scale Combustion Model)

Mixing length scale

$$\frac{1}{l} = \frac{1}{B} + \frac{1}{z+d}$$

Mixing layer growth relationship

$$\delta_{pm} \cong C\,x$$

Turbulence parameter definition

$$u' = l\omega \qquad \frac{\delta_t}{l} \propto Re_l^{-\frac{1}{2}}$$

$$\tau = \frac{\delta_t}{S_l} \qquad ; \qquad Re_l = \frac{\bar{\rho}\,u'\,l}{\mu}$$

Laminar flame speed

Shear Layer

X

Air Entrainment

Y

Fuel Mass Transfer

Injector Tip

Fuel Spray
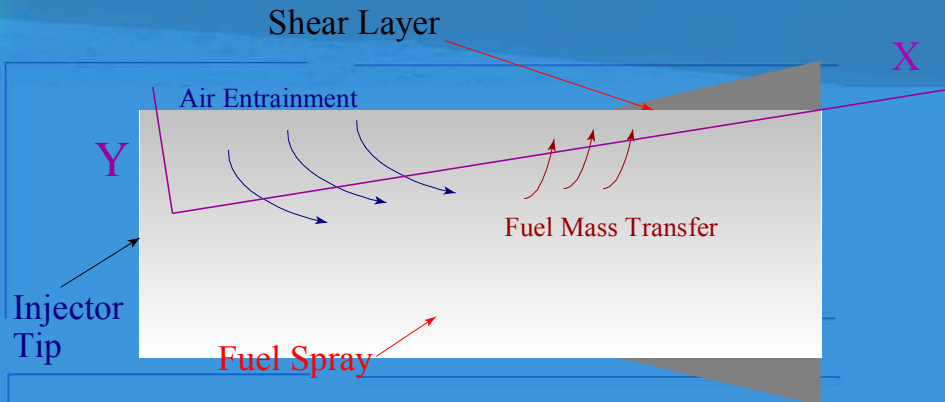
Premixed combustion model

$$\frac{dm_{en}}{dt} = FA\,\rho_u A_f (u' + S_l + U_{jet})$$

$$\frac{dm_{pb}}{dt} = \frac{m_{en} - m_{pb}}{\tau}$$
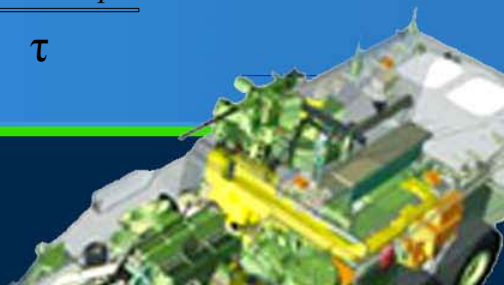
Modeling Effort – TARDEC LSCM

Mixing controlled combustion model

EGR effect

$$\frac{dm_{db}}{dt} = (m_a - m_{db})\, \omega\, \frac{\tau_{mix}}{\tau_{imp}}\, \frac{\tau_{mix}}{\tau_{wall}}\, \frac{\tau_{mix}}{\tau_{util}}\, \frac{\tau_{O2}}{\tau_{O2-base}}$$
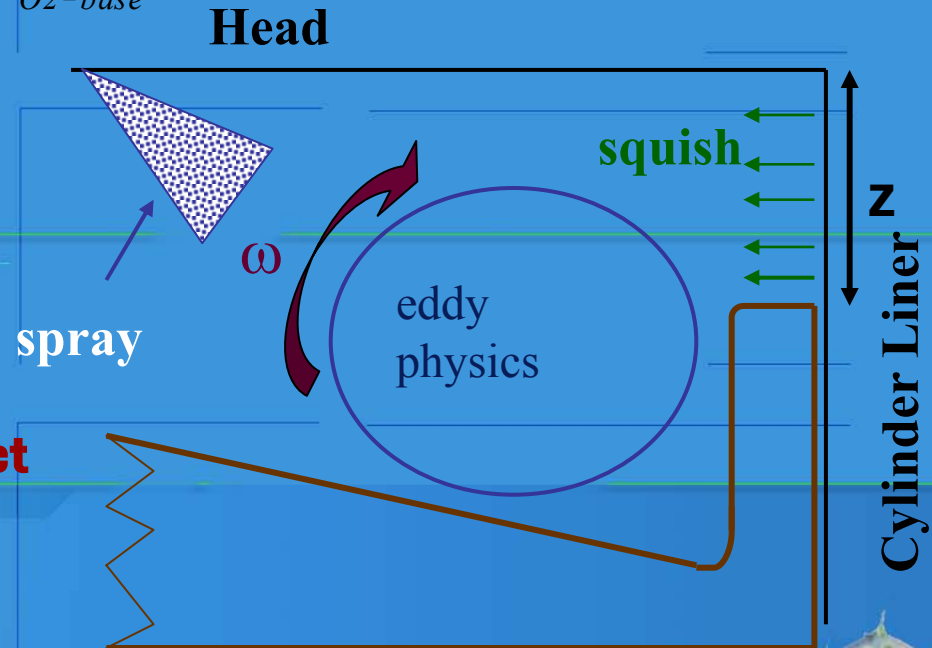
Head

Parcel 'mixedness' definition

$$\int_{t_i}^{t_i + \Delta t} \omega\, \frac{\tau_{mix}}{\tau_{imp}}\, \frac{\tau_{mix}}{\tau_{wall}}\, \frac{\tau_{mix}}{\tau_{util}}\, \frac{\tau_{O2}}{\tau_{O2-base}}\, dt = 1$$

squish

Z

Cylinder Liner

ω

spray

eddy physics

Premixed Phase Impact **EGR effect**

$$S_l = S_l\,(EGR)$$

imp : impingement (neg. for CIDI)
wall : wall effect
util : air utilization

Modeling Effort

- Laminar flame speed fundamentals
  - molecular structure, temperature, air-fuel ratio, and pressure dependence
  - experimental measurement pitfalls
    - ignition issues establishing homogeneous charge
    - recent efforts (Northeastern University and Southwest Research Institute)
- Proposed simulation-based strategy
  - matching combustion and cylinder pressure histories THROUGH JUDICIOUS CHOICE OF LAMINAR FLAME SPEED
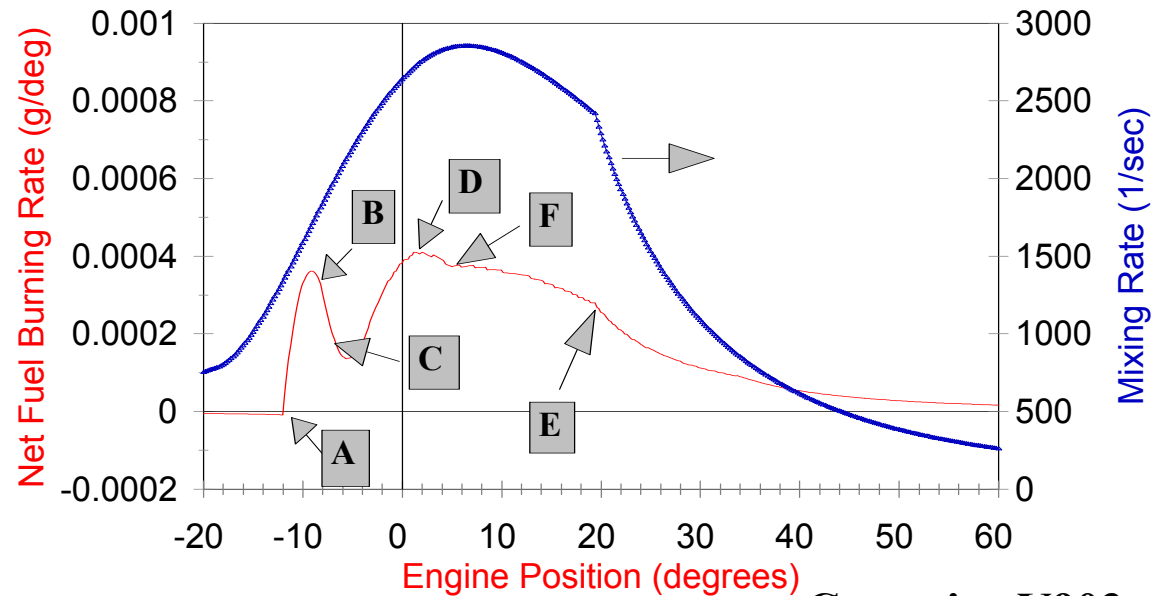   - Must be physically relevant

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Modeling Effort – Typical Diesel Combustion Behavior

A : SOC
B : total shear layer engulfment
C : start of diffusion burn
D : wall impingement
E : EOI
F : start of jet expansion

Cummins V903 Rated Speed

- Two phases – premixed and mixing (diffusion) controlled
- Premixed phase: trapped mean fuel-air pockets, turbulent flame speed (injection velocity + fuel type)
- Mixing Controlled Phase: bulk mixing rate limitation, fuel injection pressure + spray formation process (hole size, aspect ratio, nozzle type)
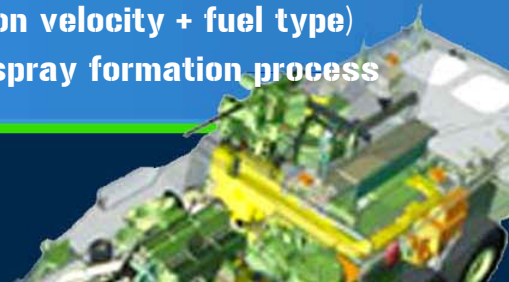
Experimental Set-up : Engines

	Ford DIATA	Cummins V903
Type	I-1	V-2
Bore x stroke (mm)	70 x 78	140 x 121
Displacement (cc)	300	1875
Fuel system	HPCR Cora II	PT – MUI (big cam)
Boost system	Shop air*	
Peak Injection Pressure (bar)	500 – 1200	600 – 1300
Nozzle geometry	6 x 0.124	7 x 0.190
Compression ratio	19.5	12.5
Speed range (rpm)	1500 – 3000	1600 - 2600

* DIATA includes manual EGR system and swirl ratio of 2.4

Experimental Set-up : Fuel Effects

Fuel Parameter	Ford DIATA	Cummins V903
Density (kg/m^3)	842	845
Cetane Number	53	47
Net Heating Value (MJ/kg)	42.8	42.6
Hydrogen (% wt.)	13.25	12.8
Sulfur (ppm)	400	1400

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- **Bulk cylinder initial conditions**
  - 800 – 1000 K
  - 30 – 100 bar
  - Air-fuel ratio 20 – 80
- **Spray tip air-fuel equivalence ratio**
  - 1.3 – 2.5
- **Injection velocities**
  - 200 – 500 m/s

Results – Matching Process
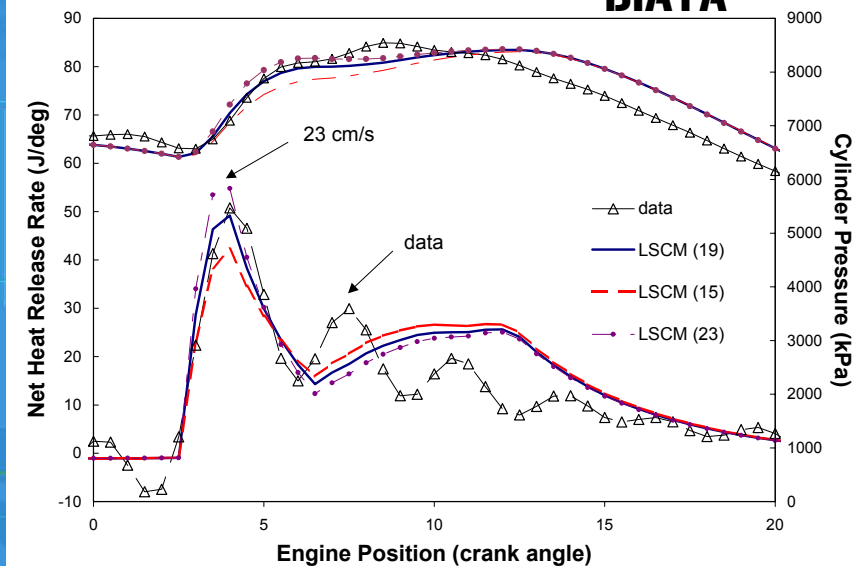
- Database of HRR and pressure profiles studied – match or mismatch
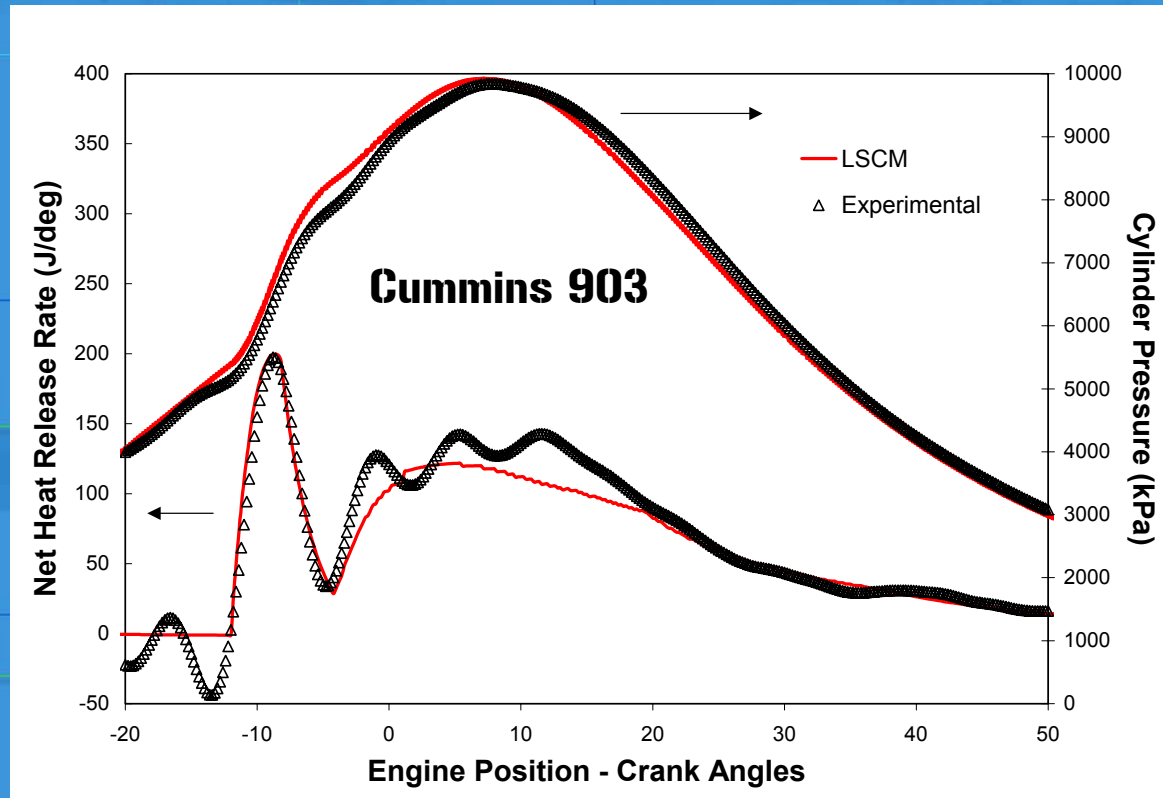- Cool flames ignored – cool flame chemistry not incorporated into LSCM

DIATA

- Laminar flame speed modulated until general heat release profile and mean cylinder pressures are 'close' to experimental profile
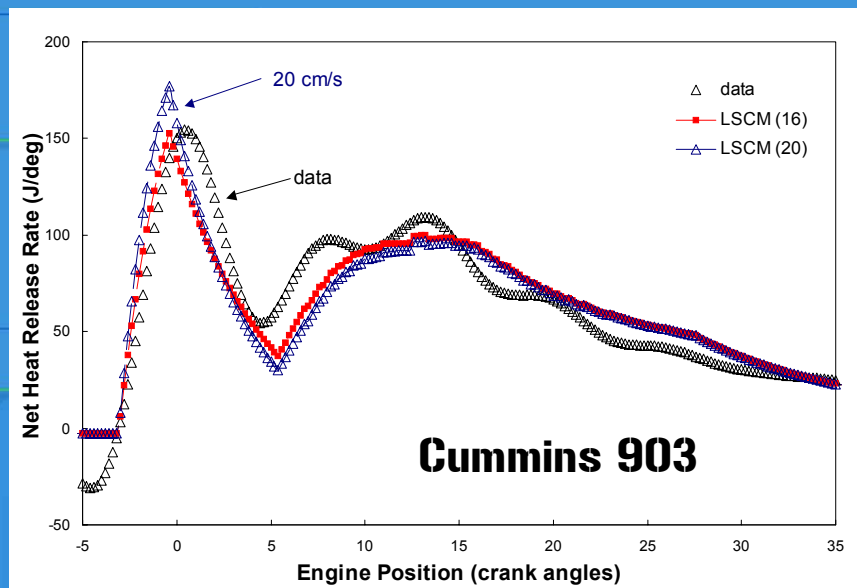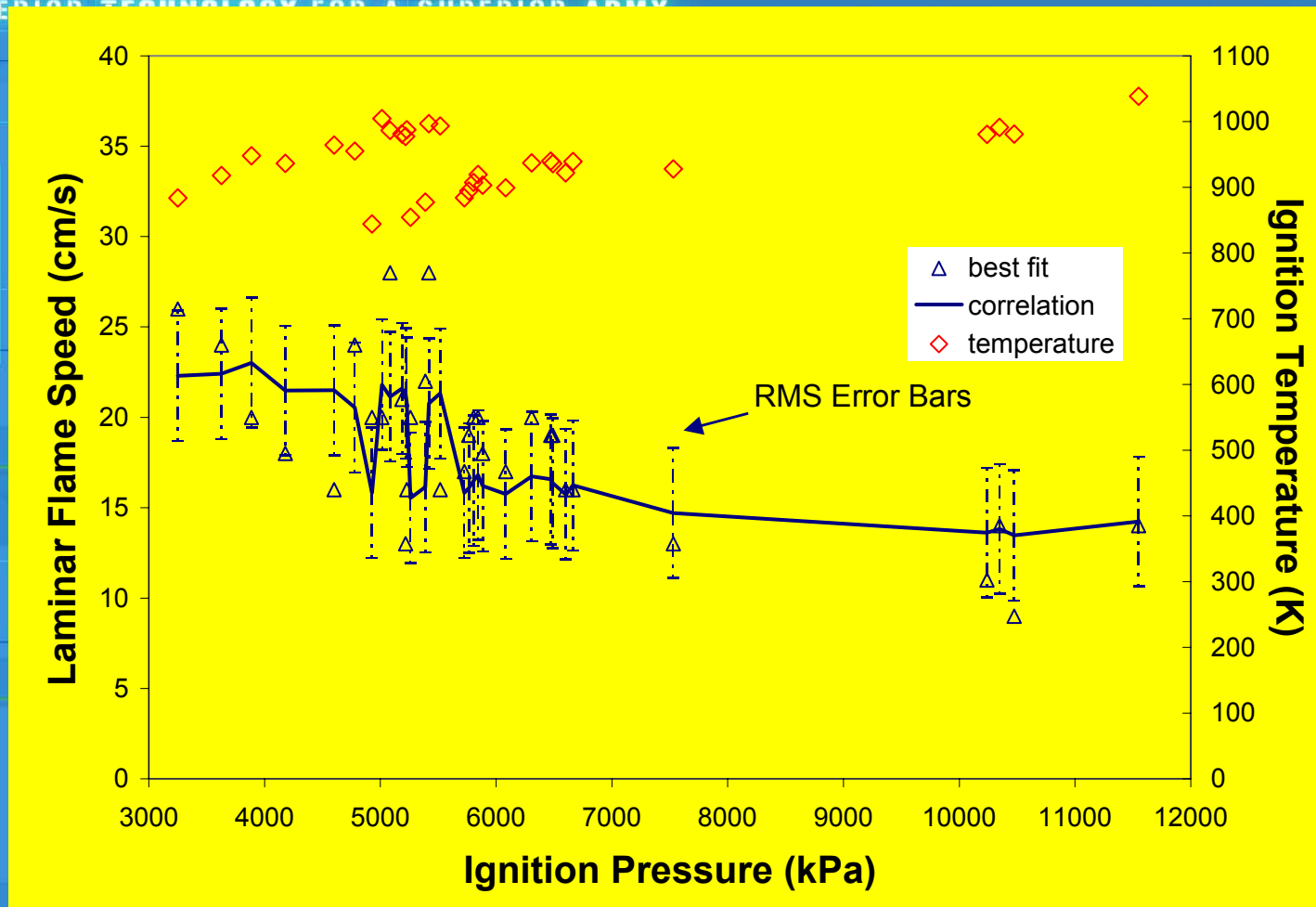

Cummins 903

Results

Results – EGR cases
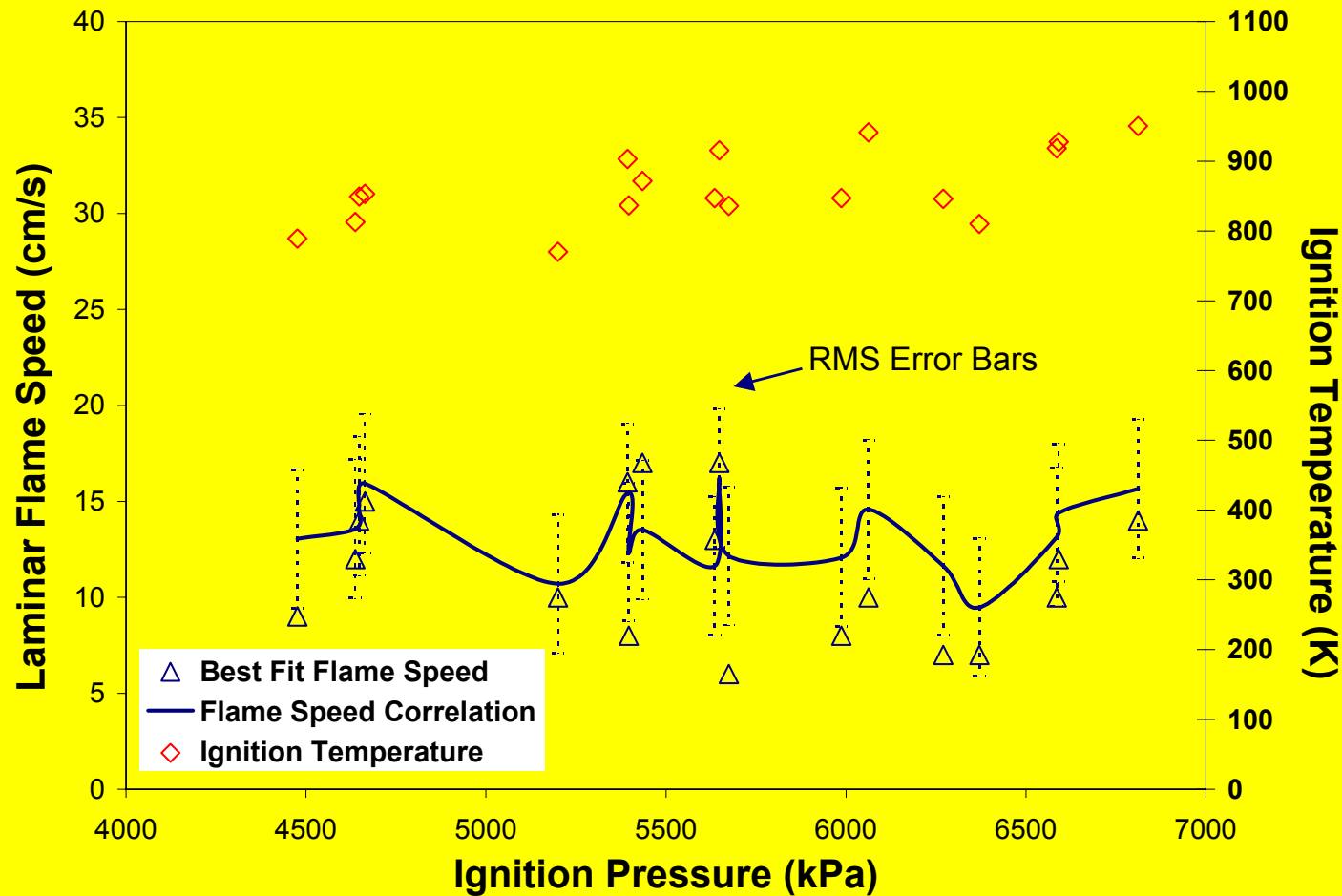
Results
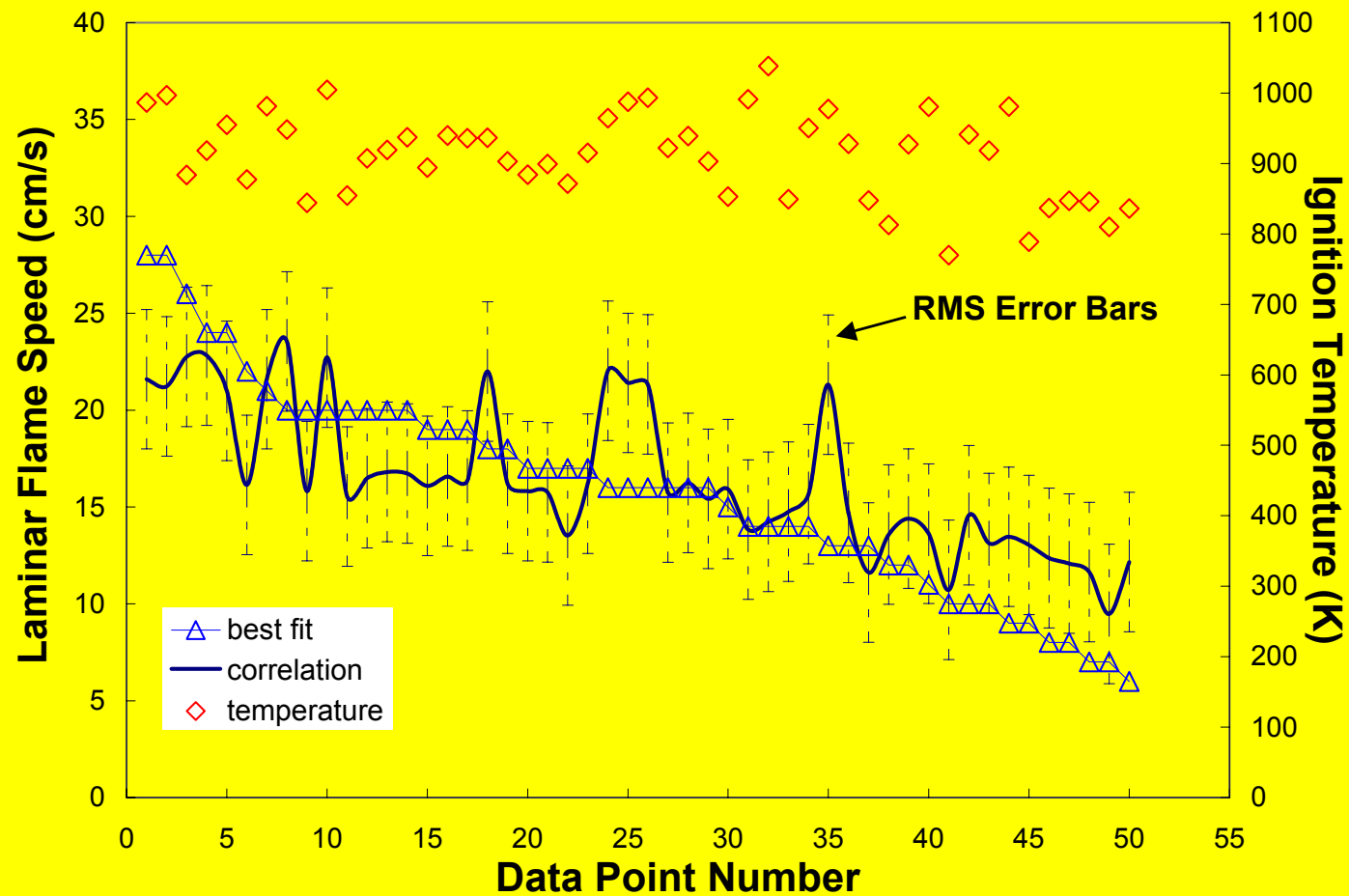
Conclusions

- Experimentally determined HRR profiles for small and large bore engines utilized to determine representative laminar flame speed
  - ❑ *First of its kind for diesel fuel*
- Study included EGR effect at light load (DIATA) : 3.6 cm/s RMS error
- Resulting Correlation ---

$$S_l = 21 \left(\frac{T}{300} \right)^2 P^{-0.6} \left(\frac{Y_{O_2}}{0.21} \right)^{0.3}$$

- First order estimate on laminar flame speed for DF-2
- Maybe employed within flamelet models (CFD)
- Currently utilized in TARDEC LSCM

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